

# On the Collapse Behavior of a Wood Arch made with Modular Hollow Blocks

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*Abstract:* - In the field of construction, wood products are known to have environmental benefits if compared with materials like steel and concrete, especially regarding the reduction of carbon emissions of the production line. Today, the wood-architecture is maintained and renewed by the marketing of components or pre-manufactured wooden frame elements. This research consists in the numerical study of a wooden arch behavior realized with hollow blocks. Initially, experimental tests have been performed on a full-scale arch model. The results of the load tests have been compared with three different FEM-analyses. In particular, in the numerical simulations the hollow blocks have been modelled once as beam elements, then as plate elements and, finally, as block elements, they distinguish for the level of accuracy and the level of calculus. Results are interesting to evaluate the better compromise between accuracy and cumbersome calculus to get a reliable modeling of these kinds of structures.

*Key-Words:* - wooden arch; modular structure; characterization; collapse tests; numerical modeling.

## 1 Introduction

Wood was one of the first building materials and has been for years the means to solve the most complex structural problems. With the advent of reinforced concrete and steel, its use has been gradually decreasing. Such decline was much greater in Italy than in other European countries, while North America has continued to use it extensively, especially in civil engineering. Only the recent development in architectural design and new construction techniques, as well as the deepening of structural analysis and the strength of wood to fire, together with the introduction of new products able to preserve the wood from degrade, allowed to regain possession of the varied architectural possibilities, the extraordinary aesthetic and full compatibility with the criteria of sustainable development that a wooden structure has to offer.

Wood is undoubtedly one of the most suitable for green building materials. The lightness, the high resistance to compression and tensile stresses, ease of processing, the impregnability by the chemical and environmental aggression and the almost absolute insensitivity to temperature changes, allow the most different structural uses. Wood is also featured by good insulating qualities, both thermal noise and a low electric conductivity.

Wood is an eco-friendly material too: the energy used in the production process is much lower than that required for the construction of houses in reinforced concrete or masonry. Demolition of wooden artefacts is cheaper and faster, it has a good resistance. It is also a material with a very low stiffness, and this allows the wood to absorb the seismic energy and the whole construction to better respond to the effects of an earthquake.

In addition, from a static point of view, wood can show excellent results also better than masonry, reinforced concrete and steel, thanks to new technical advances [1,2]. However, the decline of wood in Italy was due also to a vacuum in the national code, which has been filled only recently (EC5, DM 2008 and its new version, with new prescriptions for timber structures) [3,4].

Scientific studies have also highlighted a legislative gap regarding the evaluation of the load capacities of timber-concrete composite joints exclusively entrusted to standard shear tests on "push out" joints [5].

A key aspect in the design of timber structures deals with the choice of the mechanical and structural models that properly describe the behavior of the materials and the structural systems themselves. According to all code prescriptions of the latest European edition, actions must be assigned to one of the classes of duration of load, which are

characterized by the effect of a constant load for a certain period of time of the life of the structure. In this way it is possible to estimate the interaction between the typical temporal variation of the load in the time and the material properties.

Wood is a very particular and efficient material, different from the most commonly building materials, its structure having different and interesting characteristics, almost conflicting, like, for example, its notable strength under both compressive and tensile loads that becomes nearly unique if compared to its limited weight density. All this leads to realize structures absolutely suitable for the seismic safety too.

A disadvantage could be the degradation in the time of the mechanical characteristics of timber structures depending on the type of wood [6]. Generally, elements in wood, due to the nature of the material, can be subjected to a reinforcement intervention for several reasons: increment of the dead loads, degradation of the mechanical properties of the element or simply only to reduce excessive displacements. In particular, in recent years, also techniques born to reinforce masonry elements have been tested on wood such as Fiber Reinforced Polymers (FRP) [7], which has given excellent results in both construction techniques in the case of structural elements subject to bending.

A common application of wood was for floors and, especially in the past, as a material for arches and vaults. New low-cost solutions are quite often pursued for increasing the structural and aesthetic quality of the manufactured units. An idea of a modular component easy-to-assemble for low-cost structural arches on site, mainly for civil building applications is proposed in [8]. It could be considered a sort of dry-assembling technique typical of houses and constructions of the South of Italy, especially utilized in the past, like *Trulli* that recently have been studied regarding their static and dynamic behavior [9]. For this kind of structures also innovative methods of analyses have been proposed [10]. Interesting studies related to vaults made with dry-assembled blocks can be found in [11].

With this in mind, the present paper deals with the study of an innovative construction system for wood arches and vaults, realized utilizing wooden hollow box-shaped blocks [12-14]. These blocks, due to their shape, assure both a considerable saving of material, and the possibility of having compartments for the accommodation of facilities, as well as guarantee lightness and ease of assembly. This innovative product and the research study associated to it, therefore, wants to bring back both

the constructive system, and the material used for the structural elements.

In this paper, on the basis of the displacement and load collapse values recorded by experimental tests on a wooden arch realized with hollow elements, several numerical analyses have been performed to evaluate its structural behavior. An experimental-numerical comparison has been conducted and the results have been widely discussed in order to evaluate the better compromise between accuracy and cumbersome calculus to get a reliable modeling of these kinds of structures.

## 2 Experimental Test

The constructive system object of this analysis was designed and produced by Intini S.r.l. enterprise (Noci, Italy). The system is good to satisfy the necessity to cover spans (some of considerable size) with a structure that does not require the inclusion of intermediate supports. In this way it results in a lightweight arch easy to install by mean of its mechanical junctions.

### 2.1 The wooden arch

The arch building system considered in the present study is based on wooden hollow blocks. Important characteristic of the block is its modularity. The arch specimen consisted of 18 wooden blocks and one key block, to a depth of two blocks, with a span of 6 m and a covering of 2 m (Fig.1). The tested wooden arch was made in scale 1:1.

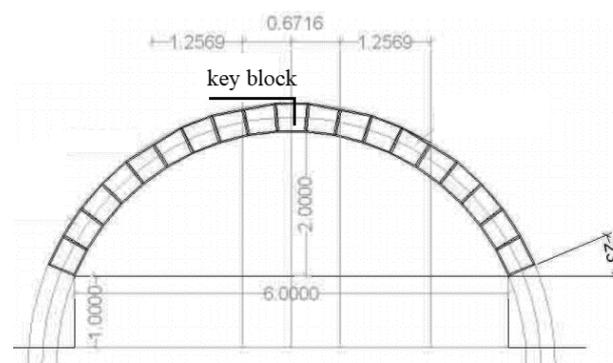


Fig.1. Geometric details of the tested arch.

The box-shaped blocks are made with plywood panels from pine (9 layers for a total thickness of 18 mm), and from birch (13 layers for a total thickness of 18 mm). The panels are then combined to form a closed box structure, which has a special feature: the connecting system (Fig.2) consists of a tooth and a cut and this allows a simple assembly of the vault.

In particular, the connecting system is constituted by a male-female joint that fits each other block. In the constructive system, the ashlar is made of birch wooden panels (13 layers for a total thickness of 18 mm). Only the key block is designed with two "female" links in order to accommodate the standard elements.

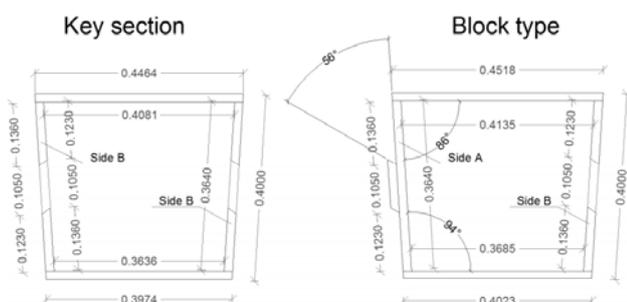


Fig. 2. Executive drawings of the blocks with the connecting system by means of male-female joints.

The panels are then arranged together so as to form a closed box-like structure (Fig.3a) with a hooking system of a male-female type that, during the assembly, allows to use fewer supports (Fig.3b). The principal characteristic of the block is, in fact, a perfect modularity, with the exception of the key element designed with two "female" connections, so as to accommodate the "block type" elements. Experimental studies have been conducted on the base material, on the individual blocks and, thereafter, on the arch prototype built in scale 1:1 to evaluate the displacements, the deformations and the maximum load to failure and to examine its compatibility with the provisions of the code in force [12]. The results of the compression tests, carried out on three specimens, showed an average value of the ultimate compressive stress equal to 27.56 N/mm<sup>2</sup>.

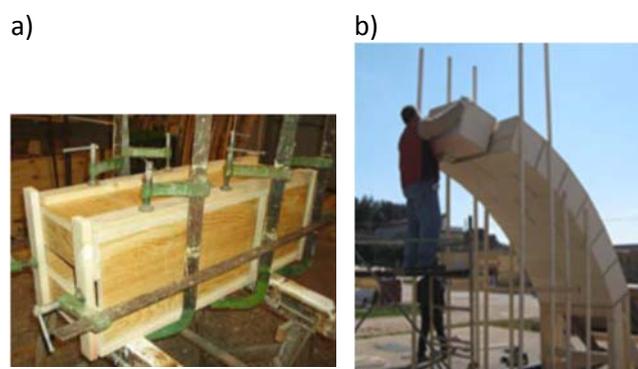


Fig.3. a) Assembling of the wooden panels to form a closed-form ashlar; b) Assembling of the arch.

## 2.2 Mechanical characterization of the blocks

The characterization tests were performed both on the wood elements in birch plywood, manufactured according to UNI EN 1058:1997 and on the hollow blocks under compressive force. In the first tests on the plywood, since the thickness was 18 mm, three sheets of plywood were used for each specimen. The sheets, after a process of scraping, assumed the thickness of 15 mm each; then they were bonded together to create a specimen having a total thickness of 45 mm (Fig.4). The results of the compression tests, carried out on three specimens, showed an average value of the ultimate compressive stress equal to 27.56 kN/mm<sup>2</sup>.

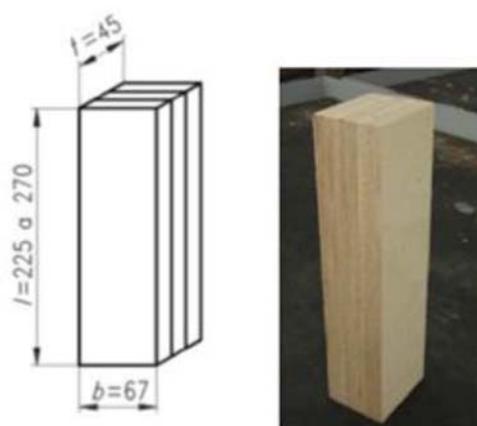


Fig.4. Wood specimen utilized for the characterization of material.

The tested blocks, as described in sect. 1.1, have the particularity of a hollow cross-section in order to give lightness and ease of assembly. The different panels constituting the block have been assembled using the same glue to fast setting the adhesive for cold hardwoods. The compression test load was applied by a hydraulic test machine on cubic specimens with dimensions 400x400x400 mm. The tests were performed on:

1. three specimens consisting of a single cubic specimen (Fig.5a);
2. three specimens each consisting of a pair of blocks (Fig. 5b);
3. three specimens each consisting of three blocks.

From the tests the following average values of the compressive ultimate forces were obtained: 358.7 kN, 237.3 kN and 210 kN.

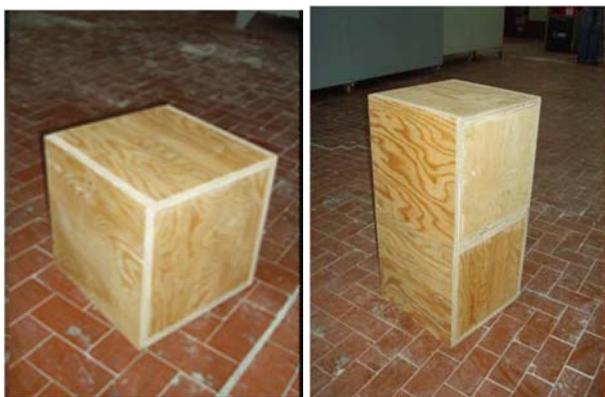


Fig.5. Wood specimen utilized for the characterization of blocks.

### 2.3 Test Set-up and experimental results

After the characterization tests on the material and on the blocks, a load test on a real arch prototype has been performed.

Two series of loading tests were performed on the arch, one with a symmetrical load keeping the arch in the elastic field, and one with the load applied in an asymmetrical position and incremented up to the collapse of the arch. In particular, Fig. 6 shows the testing set-up under a symmetrical load configuration. In Fig.6 it is possible to note that the arch was instrumented with five touch transducers of 75 mm and by two inductive transducers by 100 mm. The instrumentation was connected to a data acquisition board.

Fig. 7 shows the collapse of the arch prototype under an asymmetrical load condition.



Fig. 6. Tested arch with details of the positioning of the displacement transducers.



Fig. 7. Collapse mechanism and achievement of the hinges in the arch with an asymmetric load condition.

During the experimental test, the symmetrical loading condition was realized utilizing the three tanks full of water. In this way, three symmetrical incremental vertical forces with a maximum value of 30 kN have been applied on the arch; the arch reached the maximum load of 30 kN without generating any crisis phenomena with a residual displacement of 3.68 mm of the key section.

A second experimental test was carried out applying a non-symmetrical loading condition. In this case the structure was brought to collapse under an ultimate load condition equal to 10 kN. More in detail, the test with non-symmetric load condition has shown that the system behaved in a way similar to masonry arches. In the present case, a kinematic mechanism of collapse was reached with the achievement of four hinges in the arch, alternate at the extrados and intrados in the asymmetric loading test condition (see Fig. 7).

### 3 Numerical Study

The need to evaluate the static behavior of a mechanical system is satisfied by the analysis in which the finite element discretization of the continuous leads to a mathematical representation making it possible qualitative and quantitative analyses of the characteristics of the system in real ordinary conditions of use.

The finite element method (FEM), except in rare cases, is not an exact method, but an approximate one as the convergence of the approximation to the exact solution is derived by numerous parameters. If the model is set up correctly, the solution may be very close to the exact solution, and therefore much closer to the experimental test results. Otherwise, you may run into numerical errors due to

inaccuracies of the numerical procedures utilized, errors in its formulation, due to the use of elements that do not adequately describe the physical phenomenon, and discretization errors due to an inadequate mesh, too coarse, with elements distorted, not conformable or too disproportionate.

In this study, the modelling of the wooden arch was obtained using different element types (i.e. beams, plates or bricks) and the numerical results were compared to the better compromise between accuracy and cumbersome calculus to get a reliable modeling of the structure.

### 3.1 Beam modelling

In the case of a discretization with Beam elements the FE model of the present arch-vault consists of 19 beam elements and 20 nodes. It has been developed by Straus7 software [15].

The aim of the modeling is to give a first interpretation of the response of the structure. To this aim two load conditions utilized in the experimental tests have been added, the first represented by three vertical forces, each one of 10 kN (Fig. 8); the second one consists in a global acceleration in Y direction equal to -9.81kN, thus generating the gravitational load from the top downwards.



Fig. 8. Detail of the forces applied to the structure.

In the model the nodes have been modelled not fixed but with a different stiffness for each element, depending on the values of the bending moment obtained in a preliminary analysis.

The structure has been restrained with two simple 2D supports, in nodes 1 and 2 (Fig. 10), which allow a movement of rotation and a translation. The mechanical characteristics of the material constituting the blocks are shown in Table 1.

Table 1. Mechanical characteristics of the material utilized for the wooden blocks (beam elements).

Elastic modulus [kN/mm <sup>2</sup> ]	Poisson's ratio	Density [kg/cm <sup>3</sup> ]	Thermal expansion [1/°C]
1.11 x10 <sup>4</sup>	0.0456	6.7 x10 <sup>-4</sup>	3.5 x10 <sup>-6</sup>

The geometry is the same of the blocks utilized to build the prototype for the tests [13].

Fig. 9 shows a 3D representation of the model of the arch modelled with beam elements.

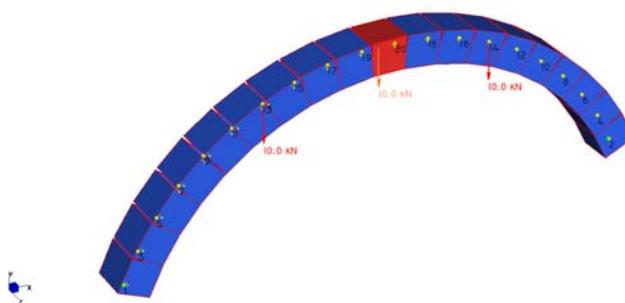


Fig. 9. 3D representation of the arch discretized with beam elements.

In the loading phase, similarly to the experimental test, the 10 kN loads have been gradually increased up to the maximum load, then followed by a discharge phase.

For the post-processing, during the evaluation and interpretation of the results of the FE analysis, Straus7 displays the results as "contours" color maps for stresses, strains, and displacements or with graphics, animations, deformed configuration and data lists.

Fig. 10 shows the deformed configuration of the structure with respect to the forces and the constraints that have been previously applied.

In a second phase, after realizing that the model gave significant bending stress we set manually the stiffness at the end of the blocks - release- initially unknown, to have a first linear displacement compatible with the experimental one.

The change of stiffness with the release was not uniform, but it increased in some points where higher values of the bending moment were found in the numerical plots. In fact, the wooden blocks were hinged and supported one another, so that they were able to transfer only compressive forces and not tensile ones.

Fig. 11 shows the bending moment acting on each element of the arch.

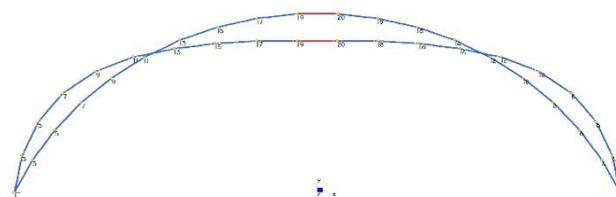


Fig. 10. Deformed shape of the structure (amplified of 5%).

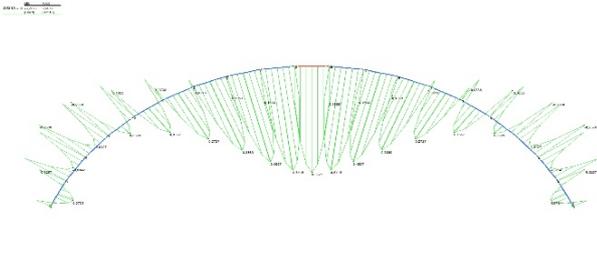


Fig. 11. Bending moment on the arch with a load equal to 24 kN.

Fig. 12 shows the “lowering” in the arch when the applied load is equal to 24 kN.

This first modeling, albeit developed in linear analysis, allowed to validate the model in such a way to approach the real structure neglecting the non-linearity. The setting of the beam elements model has been very useful for a comparison with the models successively created.

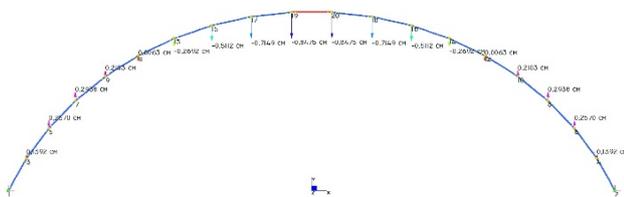


Fig. 12. Lowerings with a load equal to 24 kN.

### 3.2 Plate modelling

A second and more detailed analysis was performed using plate elements, as a result of the two-dimensional nature of the problem and because the width and the length of each block are much bigger than its thickness.

The choice to utilize Plate elements for the discretization has been dictated by the type of analysis to be carried out and, above all, by the stress variation within the blocks. In particular, having a linear stress variation a 2D finite element with a number of "sets stress" equal to three has been chosen. Therefore, for this modeling QUAD6 element (QUAD4 with a Bubble function) has been utilized to eliminate the parasite shear stresses that produced a “mesh locking” effect (Fig. 13). In total 1976 Plate elements and 2002 nodes have been utilized to model the arch.

Each block of the arch can be distinguished by two static behaviors, one bending behavior for the horizontal planes, and one membrane behavior for the two vertical surfaces (see Fig. 5). The bending behavior is hardly activated with respect to the membrane one.

Also, in this case, the same constraints, forces and load combinations utilized in the beam elements model have been applied.

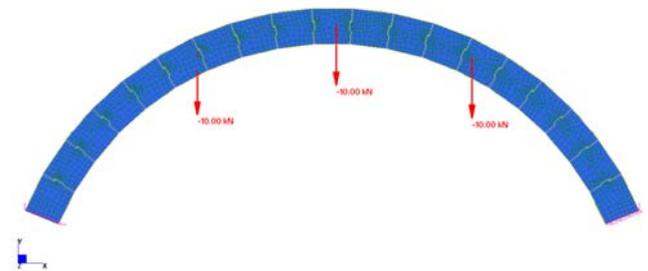


Fig. 13. "Warping" view of the arch with plate elements and applied loads.

In this modeling it has been assumed a 2D Plane Stress. In this case the nodes have only two degrees of freedom: translations in X and Y directions. It is thus required small displacements and stresses in the linear range.

An equivalent section with a membrane thickness of 38 mm and 40 mm has been utilized. The technical characteristics of wood have been set as shown in Fig. 14.

Since in this case it was interesting to find the maximum axial tensile and compression stresses, it has been helpful the representation of color maps of the axial distribution (Fig. 15). In this case too, the deformations were found to be very similar to the experimental ones. The tensile and compression stresses have been analyzed. Subsequently, the nodes have separated in correspondence of the tensile stresses where the segments detached one from the other.

Birch Plywood			
Structural		Heat Transfer	
Tables		Geometry	
Element			
Moduli: kPa		Poisson's Ratio	
E1	1,114000 x 10 <sup>7</sup>	v12	0,0456
E2	5,880000 x 10 <sup>6</sup>	v23	0,466
E3	1,410000 x 10 <sup>6</sup>	v31	0,0694
Shear Moduli: kPa		Thermal Expansion: /C	
G12	9,100000 x 10 <sup>5</sup>	α1	3,500000 x 10 <sup>-6</sup>
		α2	3,500000 x 10 <sup>-6</sup>
		α3	3,500000 x 10 <sup>-6</sup>
Damping Ratio		Density: kg/cm <sup>3</sup>	
	0,000000 x 10 <sup>0</sup>		6,700000 x 10 <sup>-4</sup>
Viscous Damping: kNs/cm <sup>3</sup>			
	0,000000 x 10 <sup>0</sup>		

Fig. 14. Mechanical characteristics of the wood utilized for the plate elements.

The values of the lowerings at the key section have been tabled, comparing the data of the

experimental test with the results of the modelling with beam and plate elements (Table 2).

Table 2. Lowerings (measured in mm) at the key section (Pot 4) and deviations %.

Load (KN)	Exp. stress	Beam Elements	Plate elements		Plate elements	
			Membrane thickness			
			40 mm		38 mm	
Key Block - Pot 4 (mm)						
6.00	-18.6	-18.0	-14.3	23%	-15.4	17%
12.00	-28.9	-34.6	-28.1	2%	-30.3	4%
24.00	-69.7	-68.0	-55.4	20%	-60.0	13%
30.00	-81.5	-84.7	-69.7	14%	-74.9	8%
25.00	-64.8	-70.5	-57.6	11%	-62.0	4%

The values are referred to Pot 4 element that is the key element (Fig. 16).

From Table 2 it is possible to notice that the deviation expressed in percentage terms with respect to the experimental values is much lower than 1% thus validating the results of the modelling.

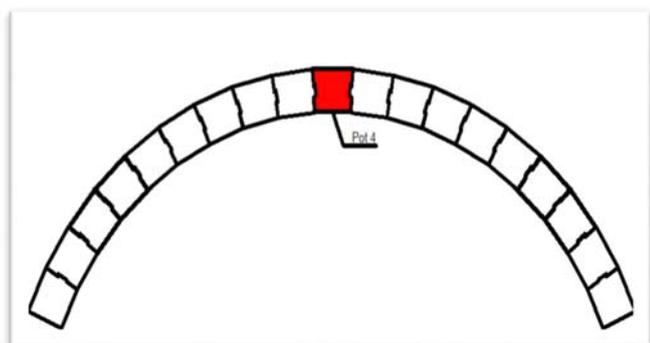


Fig. 16. Position of Pot4 element.

It was also possible to read the stress peaks in the mesh, trying to capture both the most stressed areas, likely local crisis zones, the coincidence of the maximum stress with the ultimate stress of the material (Fig. 17).

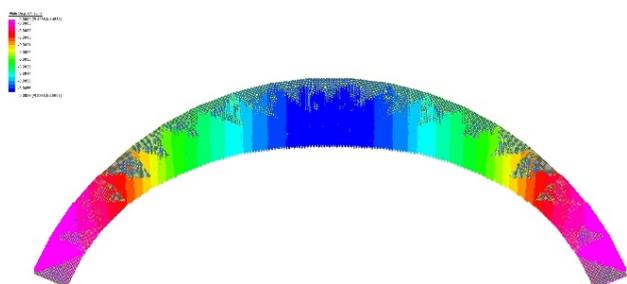


Fig. 17. "Contour" plot of the lowerings.

### 3.3 Brick modelling

The modeling with Brick elements refers to a 3D model of the arch structure.

To analyze the 3D model, we have considered the "sub-modelling", applying the "structural zooming" on the 2D plane stress elements, where the subdivision in elements adopted was dense enough for the whole response (Fig. 18).

It was possible to further the investigation by analyzing more in detail only a part of the arch and not the entire model. Specifically, the keystone and the contiguous blocks have been considered for the 3D model.

After implementing the global model, it has been paid more attention to the peak stress at the interface between the blocks in the compressed areas.

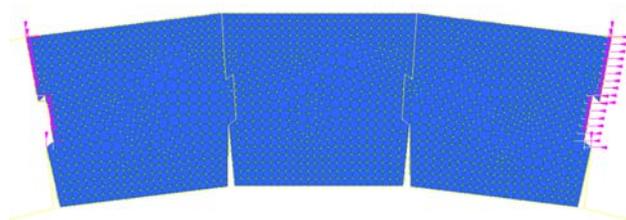


Fig. 18. "Structural zooming" of 2D plane stress elements.

In particular, we have also assessed the possible transverse stresses inside the wooden tooth, then enlarged models were realized with a few blocks going from flat elements, Plate, to 3D elements, Brick (Fig. 19).

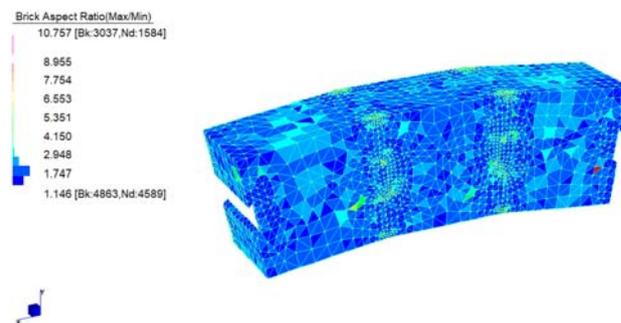


Fig. 19. Brick aspect ratio (Max/Min).

One of the most common ways to reduce the size of a finite element model, where possible, is to use the symmetry conditions. In the present case, because of its geometry, it has been possible to take into consideration one of the symmetry axes of the arch, thus agreeing to only half of the structure.

However, to analyze the 3D model, the "sub-modeling" had to be used by performing the so-called "structural zooming", first performed on 2D plane stress elements, where the adopted division into elements was sufficiently fine for the overall response. It was possible to further the investigation

without having to re-mesh and re-launch the entire model and analyzing specifically the keystone and the contiguous blocks.

The analysis confirmed the experimental findings: the connecting “teeth” of the blocks are the most stressed areas.

## 4 Conclusions

The present article proposes a different approach to the study of an innovative system for roofing structures in wood, that assures the demands in terms of code standards, especially with regard to eco-compatibility.

Wood is a perfectly eco-friendly material, from its extraction, through production and processing, to the use and disposal. The construction of halls or rooms with vaulted wooden roofs with this new construction technique would combine the high assembly capacity and would take advantage of the low thermal conductivity of the material, which ensures excellent thermal insulation.

The system offers many fields of application ranging from simple use for aesthetic purposes, to the use for structural purposes. It is easy to see how the system is aesthetically pleasing. Moreover, if properly introduced in certain contexts, it also enables the recovery of techniques of traditional building materials. The system is able to accommodate loads in safety, at least as regards the more favorable loading condition for this type of arch structures, or that of a uniformly distributed load; so it would not be ruled out its use even in the structural field, placing itself in competition with the laminated wood structures at least for certain applications such as large rooms, i.e. for sporting activities.

The analyzes carried out have enabled us to highlight different information useful for understanding the behavior of these structures. In particular, the investigations carried out considering different levels of detail allowed to clarify the potential use of this material for structural purposes.

Model validation performed on tests conducted on-site allowed us to identify the critical points of the structure collapse. A more accurate modeling can be carried out via a non-linear analysis, possibly with mechanisms of damage of the material and considering the non-linearity resulting from the degree of ductility of the connections together with further experimental data. In fact, in the present study, the damage mechanism considered provides a boundary surface defined by the parameters of tensile and compressive strength of the wood.

Globally, the knowledge gained from the present research work constitutes the beginning and the basis for analyzes to identify possible interventions of structural improvement. For more and more specific structural analyzes both in nonlinear and dynamic fields it is appropriate to conduct experimental investigations that capture the deformation capacity and strength of the joints such as to formulate reliable calculus methodologies for wood species not currently certified as structural wood.

The system here considered, in fact, collapsed not for failure of the material, but because of its connections and the joints between the various blocks, which, of course, have to be improved and modified in future studies.

For structural uses it is necessary to observe that the arch system behaves in a less efficient way for loading conditions different from the one treated in this study, however, and included in the code. Examples are the effects of an earthquake, but especially the effects of wind, a real important problem for lightweight structures.

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